

60016
Ancient Regolith Breccia
4307 grams



Figure 1: Photo of 60016 showing large glass-lined micrometeorite crater with significant spall zone. Glass lining about 0.8 cm in size. Sample is about 15 cm across. NASA S72-43840.

Introduction

Lunar sample 60016 was found near the Lunar Module and collected at the end of the third EVA. It is regarded as an “ancient” regolith breccia, presumably formed during the period of basin formation (McKay et al. 1986). It has a light grey matrix with both light and dark clasts. Ryder and Norman (1980) described this rock as a fragmental polymict breccia.

Morrison et al. (1973) and Neukum et al. (1973) studied the size distribution of micrometeorite craters, which are found on all surfaces. Figure 1 nicely illustrates a large glass-lined crater and its spall zone .

Ridley (in Butler 1972) described rare brown “staining associated with metal”. Hunter and Taylor (1981) also reported rust.

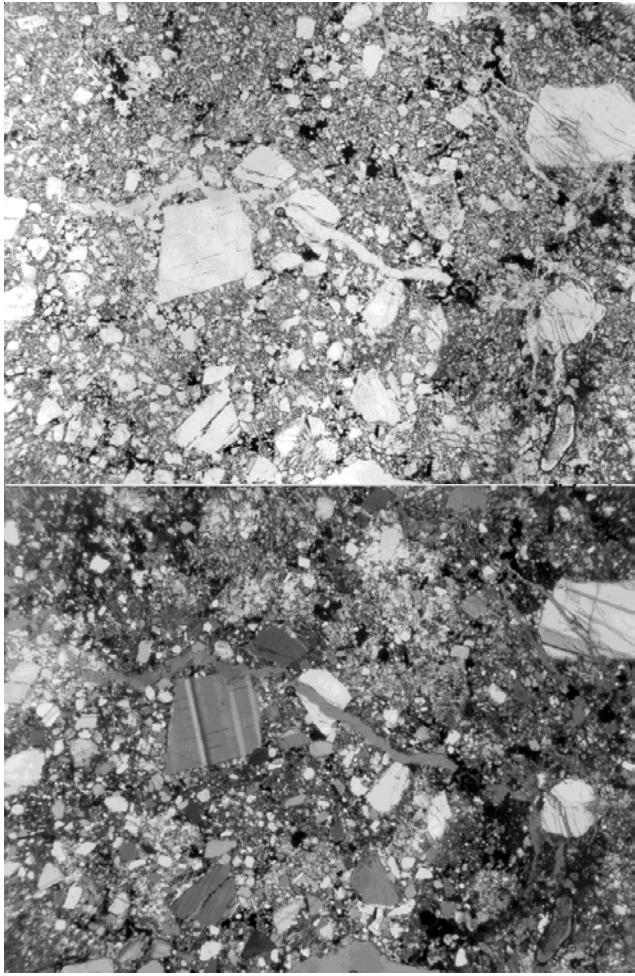


Figure 2: Photomicrographs of thin section 60016. Top is plane polarized light; bottom is partially-crossed polarized light. NASA S72-45690 and 45695. Scale is 2.5 x.

Mineralogical Mode for 60016

(from Simon et al. 1988)

	20-90 micron	90-1000 micron
Matrix < 20 micron	39.3 %	
Mare basalt	0	0
KREEP basalt	0	0
Feldspathic basalt		0.6 %
Plutonic rock frag.	0.3 %	2.7
Granulite		3.4
Poik. rocks	0.2	2
Impact melts	0.2	7.3
Regolith brec.	0.1	0.5
Agglutinate	0.5	2.1
Plagioclase	18.2	9.6
Olivine	3	0.6
Pyroxene	2.7	0.6
Opaques		0.1
Glass	2.8	3

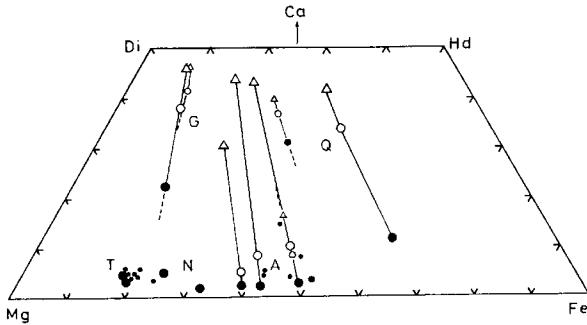


Figure 3: Pyroxenes in 60016 (some inverted). (Takeda et al. 1979).

Petrography

Although 60016 has been studied by many investigators, it has not had an overall petrographic description. Ryder and Norman (1980) found that it was friable with a porous clastic matrix with seriate grain size from several mm downwards. It is polymict with lithic clasts including cataclastic and recrystallized anorthosite, coarse-and fine-grained poikilitic impact melt, granoblastic material, noritic anorthosite, dark matrix breccias, and several types of glass fragments in various stages of devitrification. Nearly all the dark matrix clasts are aphanitic melts.

60016 has very low maturity ($\text{Is}/\text{FeO} = 0.5$) and less than 1 % agglutinates (McKay et al. 1986). Simon et al. (1988) also reported very little “fused regolith” component. Both McKay et al. and Simon et al. determined the mineralogic mode for 60016, but without apparent agreement (compare tables). McKay et al. did find agreement using three different techniques.

Mineralogy

Pyroxene: Takeda et al. (1979) reported pyroxene analyses (figure 3).

Plagioclase: Johan and Christophe (1974) found that plagioclase was An_{96-98} .

Metal: Misra and Taylor found the metallic iron grains were uniformly $\text{Ni} = 6 \%$, $\text{Co} = 0.3-0.4 \%$. Hunter and Taylor (1981) also reported “rust” around iron grains within 60016.

Glass: Wentworth and McKay (1988) found that 60016 did not contain glass with mare basalt composition, but did include glasses with KREEP, LKFM and

highland basalt composition. A few of the glass particles had high Mg/Fe ratios.

Significant Clasts

White Granoblastic ,51 ,53

Figures 9 and 10 show a large white clast (>1 cm). There is an analysis of this clast by Wanke et al. (1975)(figure 5) and the granoblastic texture is illustrated in figure 6. But is otherwise unstudied.

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Korotev(1996) found one “unusually mafic glass breccias” clast with high Sc, but low Sm (table 2, figure 8).

Chemistry

In general, analyses of the matrix of 60016 agree and are similar to bulk soil (Table 1). Korotev (1996) analyzed 2 splits of matrix and ~20 clasts (figure 8). One unusually mafic glass breccia clast had high Sc, but low Sm. Wanke et al. (1975) analyzed a large white clast and two REE-rich clasts (figure 5) as well as the matrix. Krahenbuhl et al. (1973) found enrichments in volatile elements indicating exposure to a “fumarolic component”. Jovanovic and Reed (1976) reported Ru and Os.

Goel et al. (1975) determined the nitrogen content of both light and dark lithologies of 60016 (light = 44 ppm; dark = 22 ppm; average 30 ppm). This is significantly less than for soils.

Mineralogical Mode for 60016

(from McKay et al. 1986)(20-500 micron)

	Thin Section	Freeze/Thaw	Ultrasonic
Mare basalt	0	0	0
KREEP basalt	0	0	0
Plutonic rock frag.	9.9	8.8	5.2
Other lithic	4.7	0.7	1.8
Granulitic	0	0.4	0.9
Poik. Rocks	3.7	2.9	3.3
Subophitic	3.7	9.5	8
Intergranular	4.2	2.3	1.6
Intersertal	0	0.2	0.2
Vitric breccia	5.2	2.1	3.9
Frag. Breccia	0.5	2.8	3
Plagioclase	44.5	43.5	44
Olivine	7.3	5.9	7.4
Pyroxene	1.1	3	3
Opacites	0	0.3	0.4
Glass	14.2	17	16.2
Agglutinate	0.5	0.2	0.2
Spheres	0.5	0.4	1.2

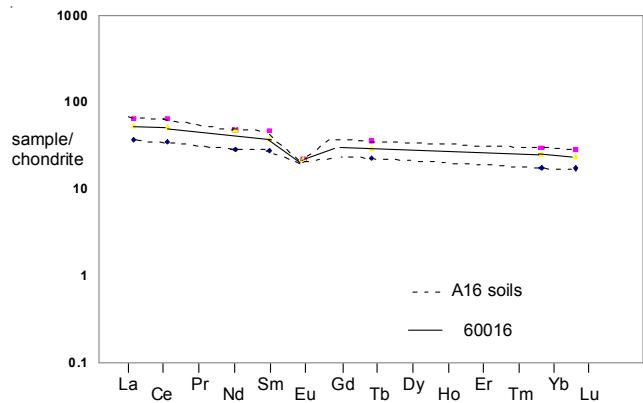


Figure 4: Bulk analysis of 60016 compared with Apollo 16 soil (see table 1).

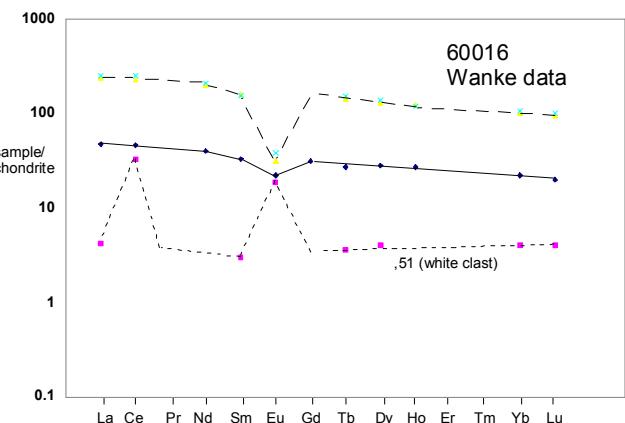


Figure 5: Normalized rare-earth-element diagram for 60016 and its clasts (Simon et al. 1988 and Wanke et al. 1975).



Figure 6: Photo of large white clast with granoblastic texture. Thin section 60016,98. About 2 mm across.

Table 1. Chemical composition of 60016.

reference	McKay 86				Korotev 96	Krahenbuhl73	Wanke 75		Taylor 74	McKinley84	Simon 88	Garg76
weight							,51	,22	,48	(ave)	161.9 mg	
SiO ₂ %							44.3	43	44.7	(c) 45	(b) 46.3	
TiO ₂							0.27			(c) 0.29	(b)	0.49 (c)
Al ₂ O ₃							29.5	20	15.9	(c) 28.2	(b) 16.4	30.1 (c)
FeO	4.47	4.6	(c) 4.13	(c)			4	7.4	11.5	(c) 4.28	(b) 12	4.33 (c) 4.41
MnO							0.063	0.093	0.12	(c)	0.13	0.049 (c)
MgO							3.8	7.63	12.4	(c) 5.51	(b) 12.9	5.6 (c)
CaO	15.7	15.3	(c) 16	(c)			17.2	11.9	10.8	(c) 15.9	(b) 11.2	17.2 (c)
Na ₂ O	0.47	0.49	(c) 0.5	(c)			0.31	0.49	0.6	(c) 0.43	(b) 0.62	0.51 (c)
K ₂ O							0.01	0.29	0.33	(c) 0.1	(b) 0.34	0.081 (c)
P ₂ O ₅												
S %												
sum												
Sc ppm	6.72	6.81	(c) 6.59	(c)			7.43	13.6	15.6	(c) 10	(b)	6.3 (c) 6.4
V										29	(b)	23 (c)
Cr	545	550	(c) 542	(c)			630	1000	1530	(c)		470 (c) 481
Co	24.5	30.3	(c) 17.7	(c)			6.19	42.3	105	(c) 28	(b)	28.4 (c) 25.3
Ni	318	445	(c) 207	(c) 265		(a)		740	1950	(c) 330	(b)	410 (c)
Cu										6	(b)	
Zn							7.55	(a)				
Ga												
Ge ppb							960	(a)				
As												
Se							182	(a)				
Rb							2.6	(a)				
Sr	180	170	(c) 202	(c)			190	160		(c) 1.91	(b)	3.9 (c)
Y										42	(b)	130 (c)
Zr	140	150	(c) 147	(c)						158	(b)	140 (c) 166
Nb										12	(b)	
Mo												
Ru												
Rh												
Pd ppb												
Ag ppb							5.5	(a)				
Cd ppb							172	(a)				
In ppb												
Sn ppb												
Sb ppb							3.74	(a)				
Te ppb							30	(a)				
Cs ppm	0.11	0.16	(c)				0.135	(a)		0.1	(b)	0.11 (c)
Ba	103	150	(c) 112	(c)				500	650	(c) 173	(b)	130 (c)
La	9.71	12.6	(c) 10.19	(c)			0.99	55.9	58.5	(c) 13.3	(b)	11.1 (c)
Ce	25.4	32	(c) 26.2	(c)			20	138	151	(c) 38.4	(b)	28 (c) 25.3
Pr										4.95	(b)	
Nd	15	22	(c)					90	95	(c) 19.2	(b)	18.1 (c)
Sm	4.43	5.68	(c) 4.69	(c)			0.45	23.2	22.9	(c) 5.21	(b)	4.92 (c)
Eu	1.2	1.235	(c) 1.22	(c)			1.06	1.76	2.14	(c) 1.17	(b)	1.25 (c) 0.99
Gd										6.34	(b)	6.2 (c)
Tb	0.82	1.02	(c) 0.95	(c)			0.13	5.11	5.57	(c) 0.99	(b)	0.99 (c) 1
Dy							0.94	31.7	33.4	(c) 6.2	(b)	6.9 (c)
Ho								6.8	6.7	(c) 1.52	(b)	1.5 (c)
Er										4.28	(b)	
Tm										0.65	(b)	
Yb	3.03	4.03	(c) 3.36	(c)			0.68	16.2	17.3	(c) 3.94	(b)	3.7 (c)
Lu	0.43	0.553	(c) 0.45	(c)			0.1	2.27	2.46	(c) 0.61	(b)	0.48 (c) 0.55
Hf	3.3	4.34	(c) 3.56	(c)			0.56	17.3	19.1	(c) 3.59	(b)	3.7 (c) 3.5
Ta	0.4	0.52	(c) 0.39	(c)			0.03	2.03	2.37	(c)		0.43 (c)
W ppb												
Re ppb							0.79	(a)				
Os ppb												
Ir ppb	7.6	10.1	(c) 5.1	(c)	5.66	(a)		15	36	(c)		6.4 (c)
Pt ppb												
Au ppb	4.6	19	(c) 4.4	(c)	5.91	(a)		15	36	(c)		1.6 (c)
Th ppm	1.64	2.31	(c) 1.73	(c)				6.9	7.8	(c) 2.1	(b)	1.46 (c) 1.2
U ppm	0.42	0.53	(c) 0.42	(c)	0.655	(a)				0.51	(b)	0.48 (c)

technique: (a) RNAA, (b) spark source mass spec., (c) INAA

Table 2. Composition of clasts 60016.

reference	Korotev96 weight SiO ₂ % TiO ₂ Al ₂ O ₃ FeO MnO MgO CaO Na ₂ O K ₂ O P ₂ O ₅ S % sum	clast glass beads	Schearer90 (b) 1.33 16.76 10.8 0.27 17.84 11.1 0.4 0.03 0.02	Wentworth88 (b) 48.3 0.73 12.69 16.37 0.27 7.97 11.96 0.1 0.04 0.04
Sc ppm	25.2	(a) 21 74	(c)	
V	2130	1682		
Cr	20.3	4		
Ni	70			
Sr	160	130		
Y				
Zr		376		
Nb				
Ba	84	434		
La	4.52	34.2		
Ce		84.4		
Pr				
Nd		50.3		
Sm	2.81	14.1		
Eu	1.19	0.68		
Gd				
Tb	0.67			
Dy		19.3		
Ho				
Er		10.6		
Tm				
Yb	2.48	9.7		
Lu	0.36			
Hf	2.41			
Ta	0.26			
W ppb				
Re ppb				
Os ppb				
Ir ppb	2.1			
Pt ppb				
Au ppb	0.9			
Th ppm	0.55			
U ppm	0.16			
technique	(a) INAA, (b) elec. Probe, (c) ion probe			

Other Studies

McKay et al. (1986) reported the rare gas content and isotopic ratios. The high ⁴⁰Ar/³⁸Ar ratios and presence of “fission Xe” led these authors to conclude that it is an “ancient regolith breccia”.

Adams and McCord (1973) and Charette et al. (1976) determined the optical spectra.

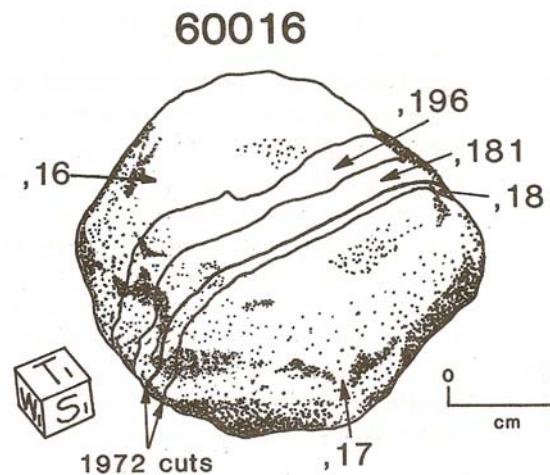
60016 was used for various magnetic measurements (Nagata et al. 1974, Huffman et al. 1974, Cisowski et al 1975 and others). I don’t think they found anything!

Processing

Fruland (1983) included 60016 in the regolith breccia guidebook. Martinez (1985) mapped the slabbed surfaces (see figures 9 – 16). There are three slabs of 60016 and 43 thin sections.

60016 has been the subject of a “consortium” led by Basu.

There are two public display samples for 60016.



Radiogenic age dating

Weber and Schultz (1978) reported K-Ar ages of 3.8 +/- 0.1 b.y. Cohen et al. (2006, 2007) reported Ar/Ar ages for two clasts (~3.8 b.y.).

Cosmogenic isotopes and exposure ages

Weber and Schultz (1978) and Eugster et al. (1999) reported a cosmic ray exposure age of 2.2 +/- 0.6 m.y. (roughly South Ray Crater age?).



Figure 7: Band saw cut of second slab (,181) from 60016,16 in 1984. Cube is 1 inch. NASA S84-40925.

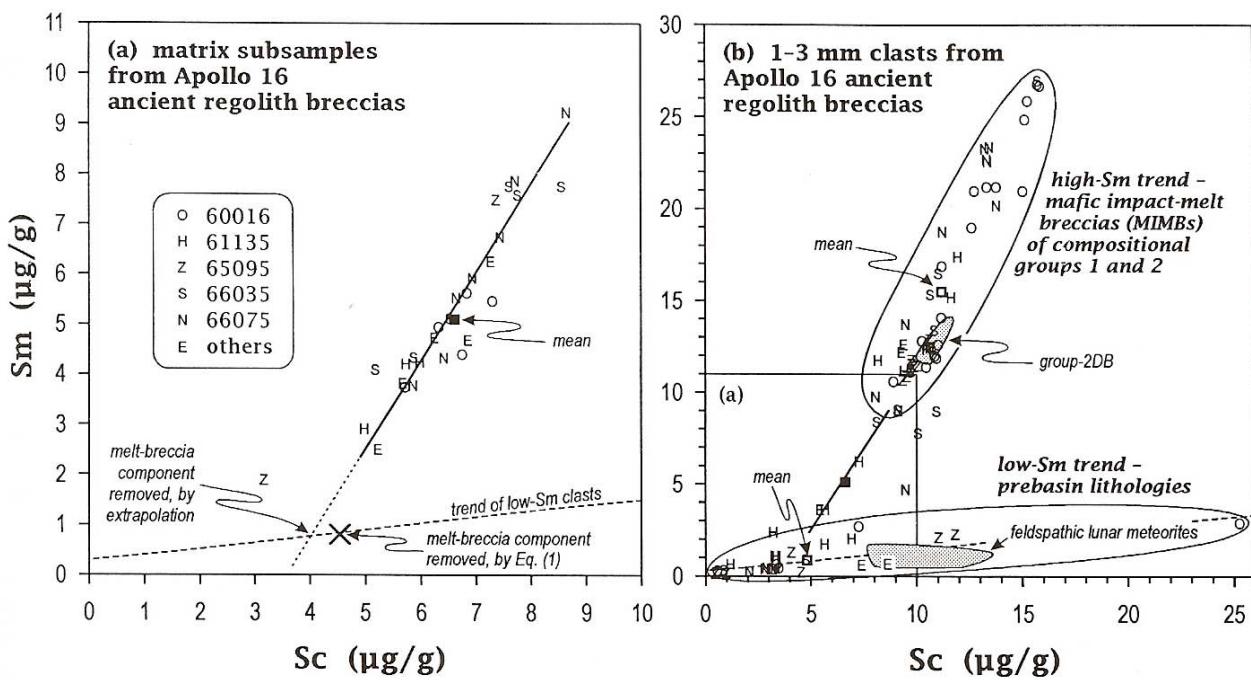


Figure 8: Chemical composition of ancient regolith breccia and clasts (Korotev 1996).

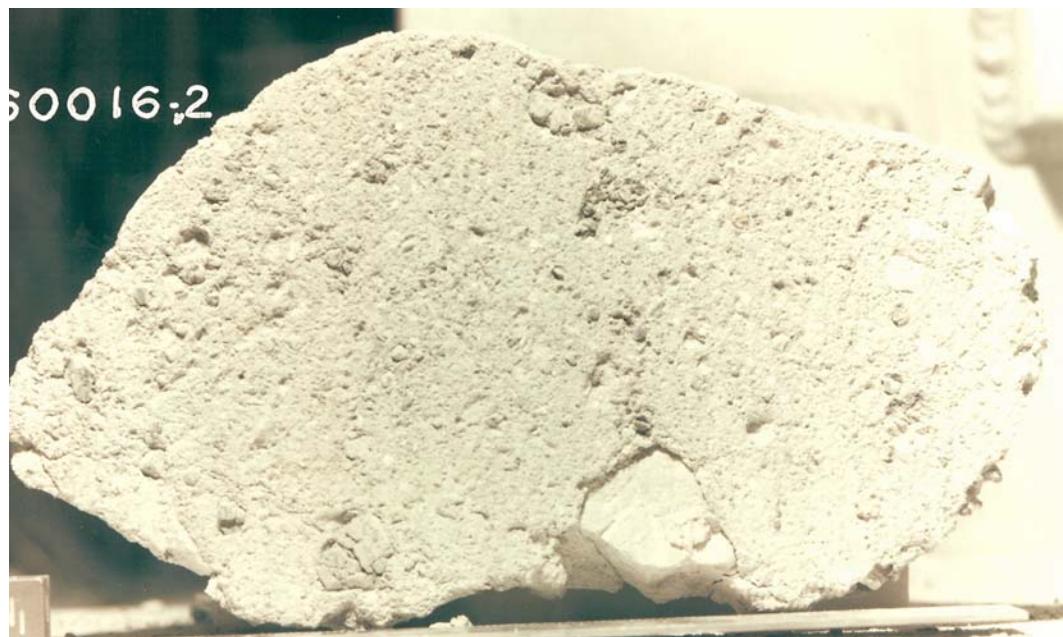


Figure 9: Photo of sawn surface of butt end (.17) of 60016 after first sawcut showing large white clast (1.5 cm). S73-21532

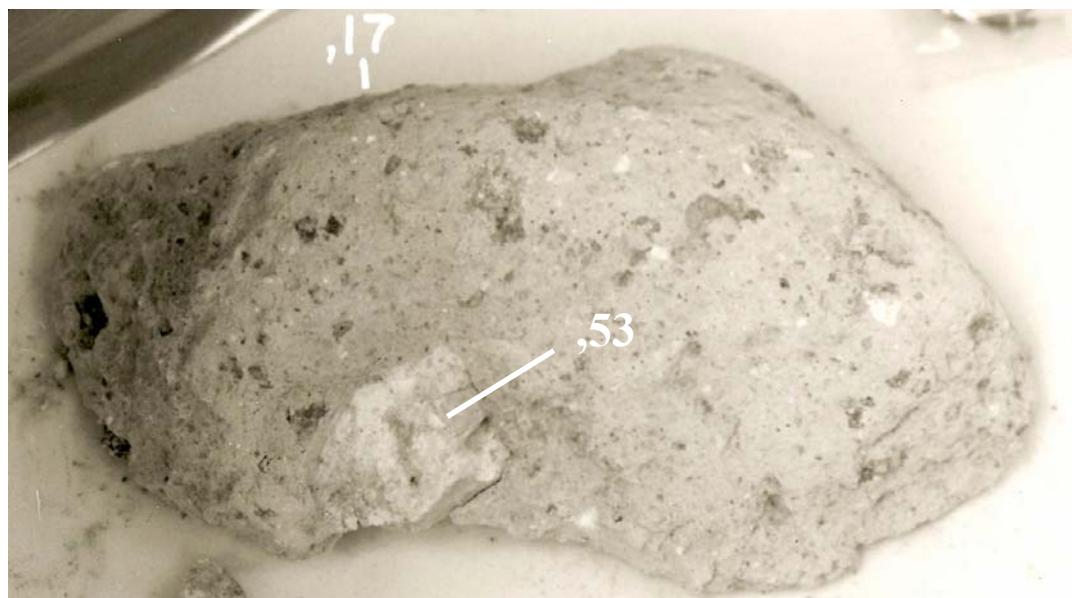
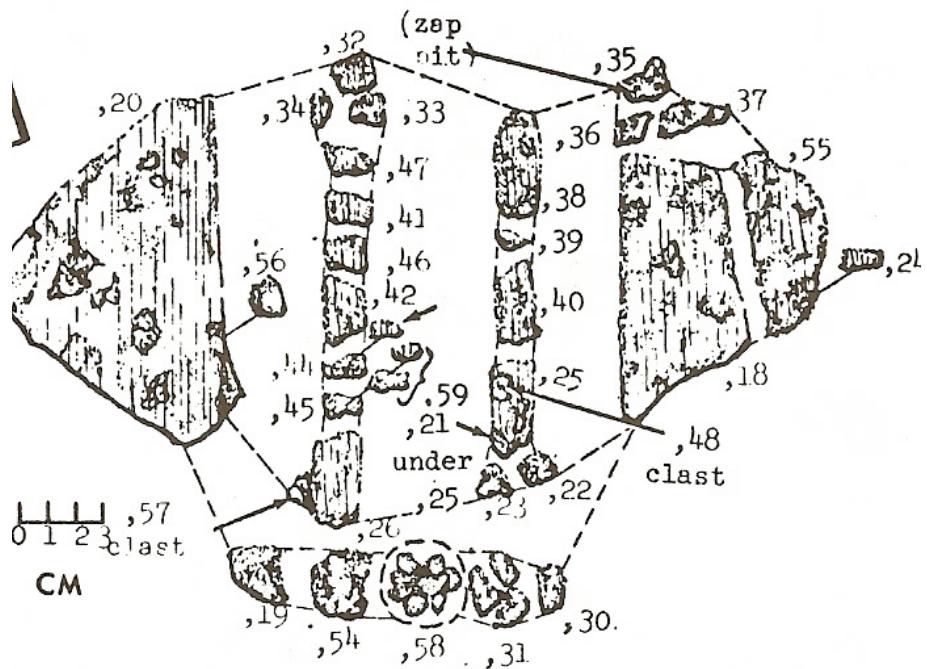


Figure 10: Photo of exterior surface of butt end (.17) showing large white clast (.51 and .53). S73-22564. Sample is about 6 inches long.



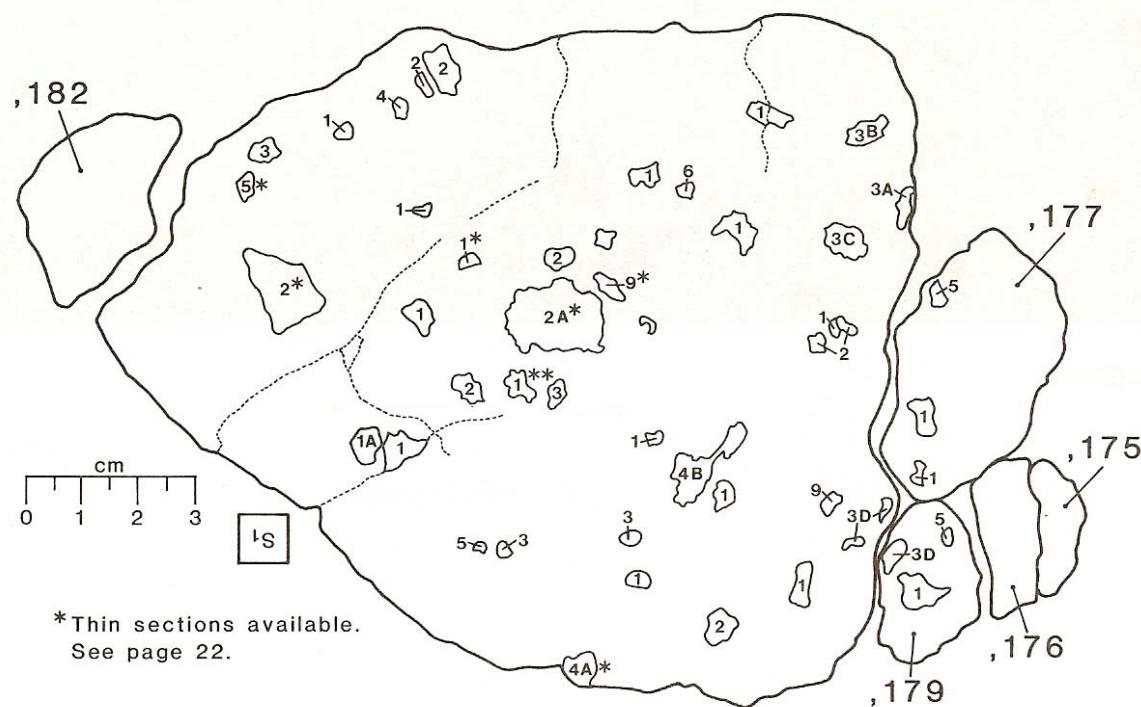
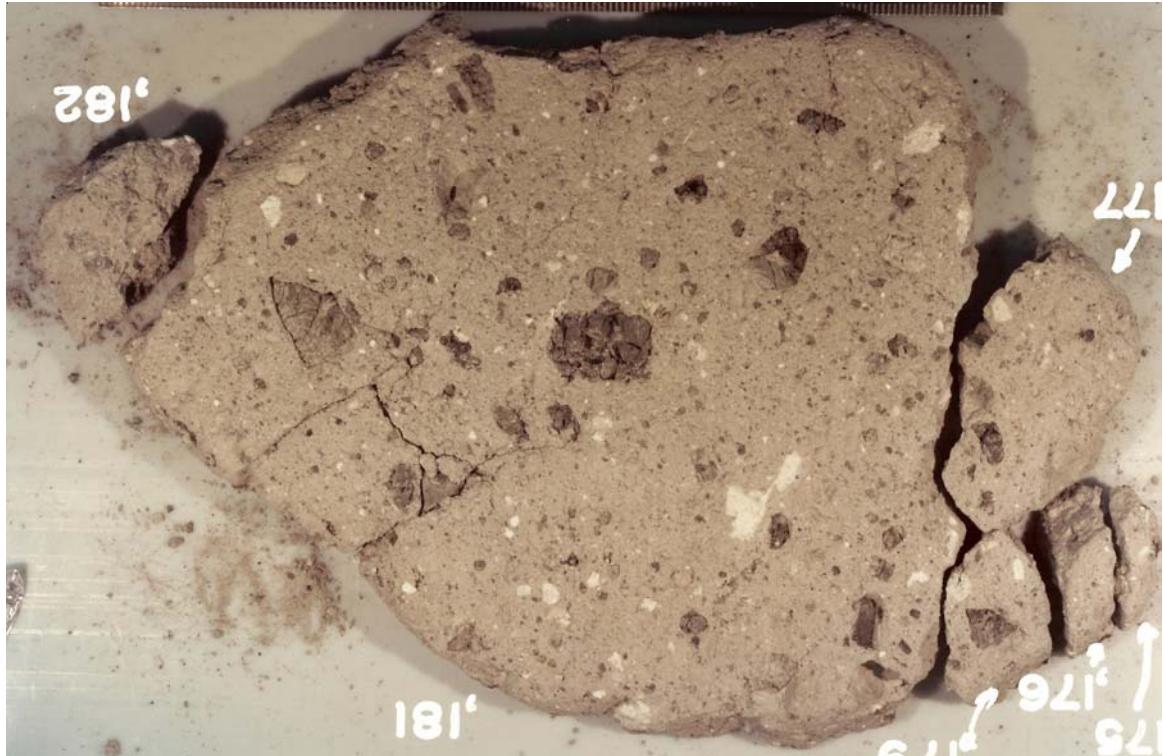
Figure 11: First slab and columns cut from 60016 in 1973. Cube is 1 cm. NASA S73-15151.



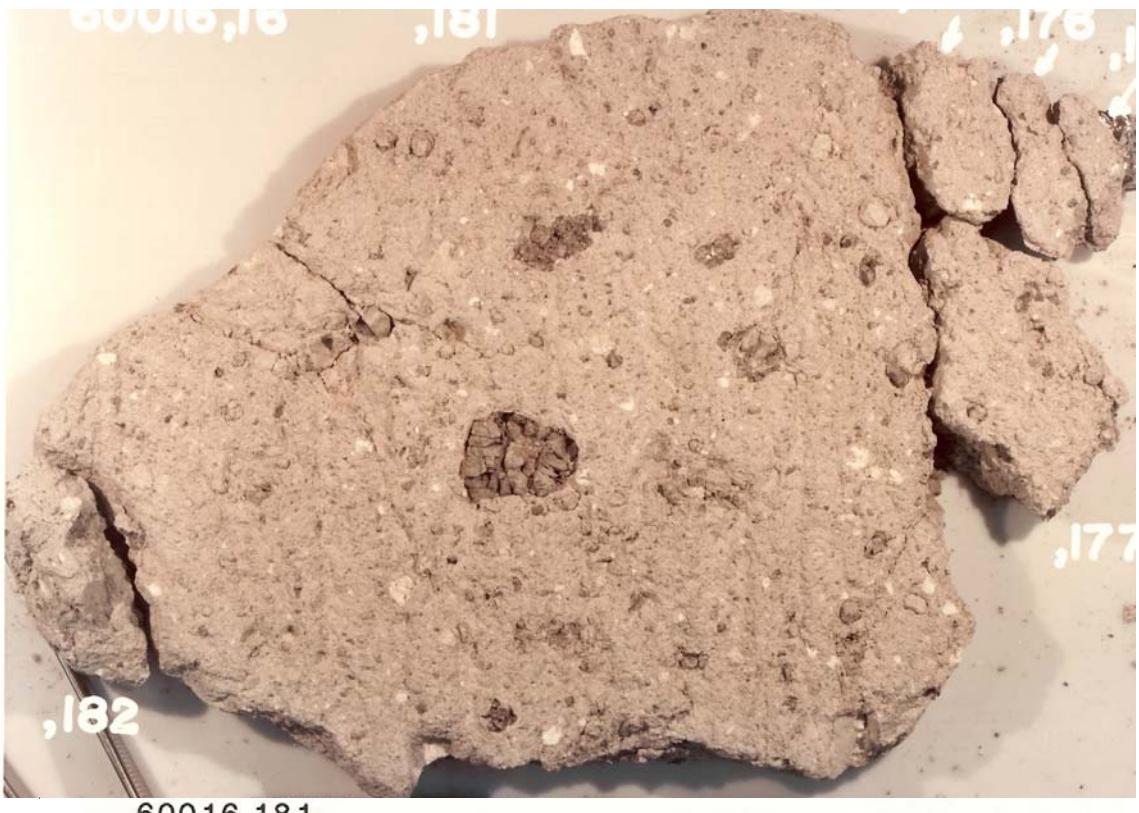
note: Splits ,21 ,23 ,39 and ,44 were used to make thin sections.



Figure 12: Photo of sawn surface of 60016,16 after first slab removed. S78-34417



*Figure 13: Photo and sketch of second slab (181) cut from 60016,16 (Martinez 1985). S84-40923.
Compare with figure*



60016,181

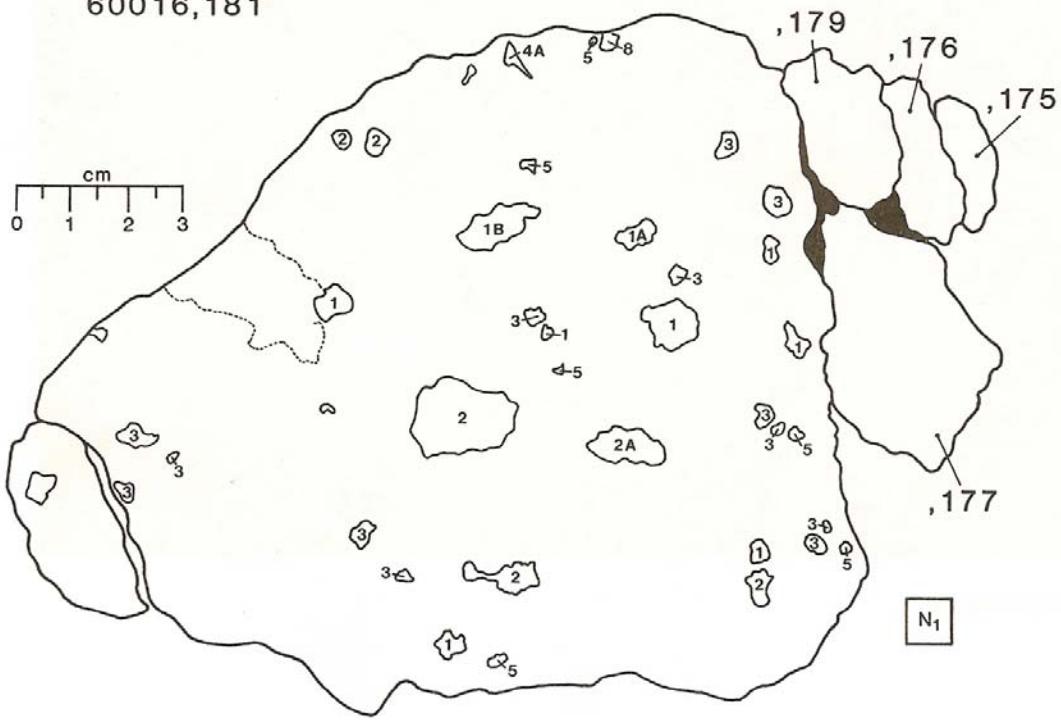


Figure 14: Photo and sketch of backside of second slab (,181) of 60016 (Martinez 1985). S84-40922.

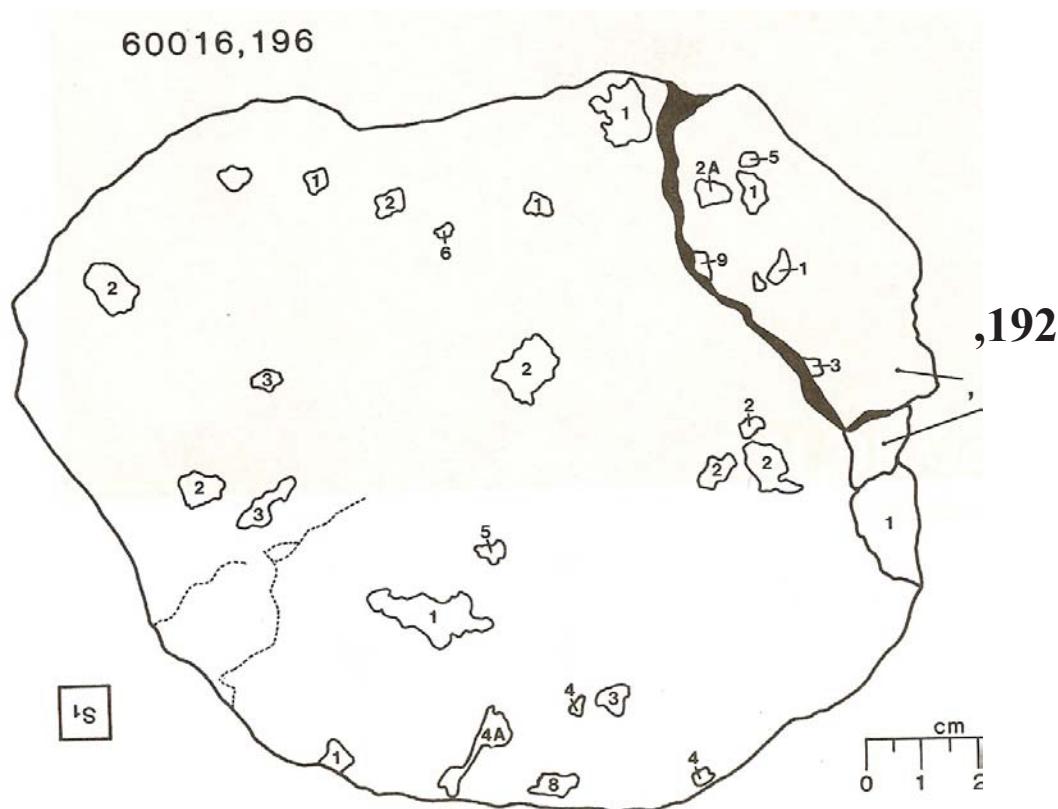
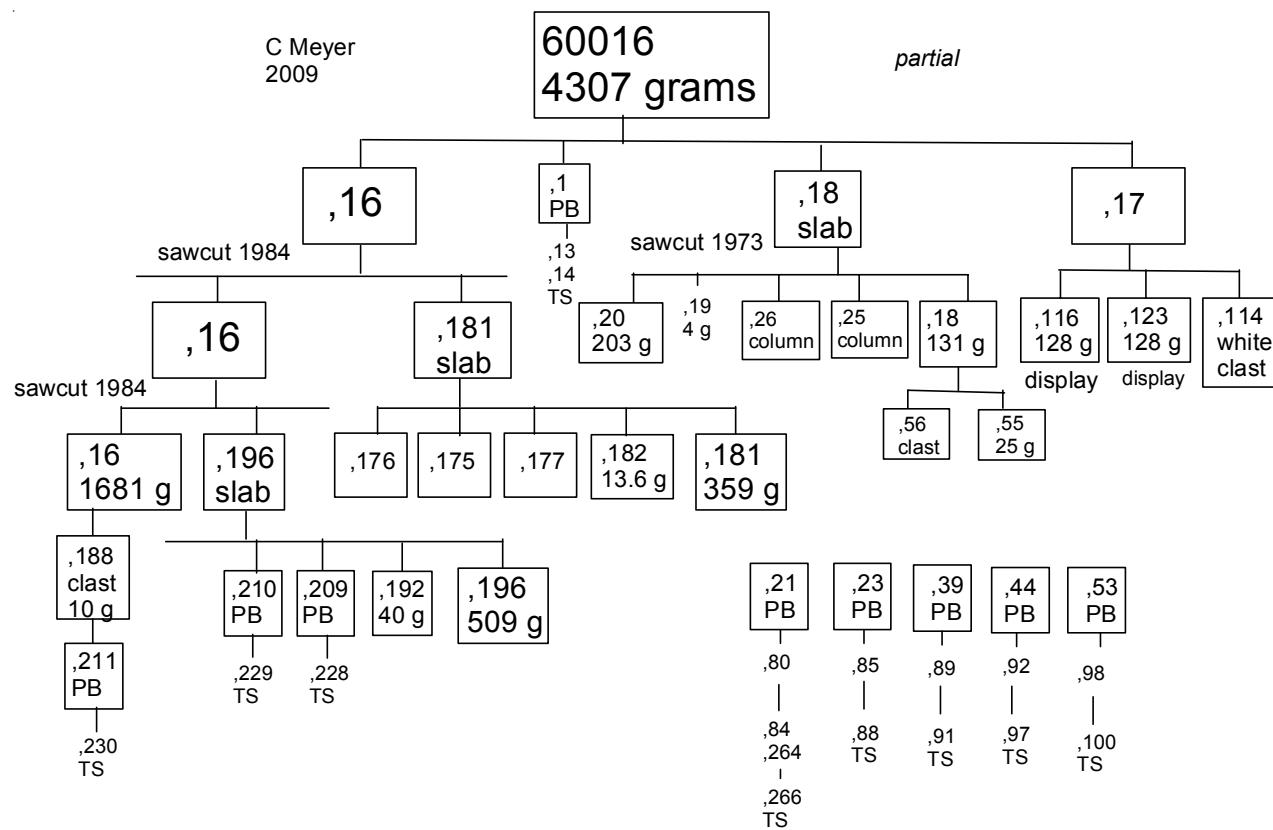


Figure 15: Sketch of slab (196) showing location of small clasts (Martinez 1985).

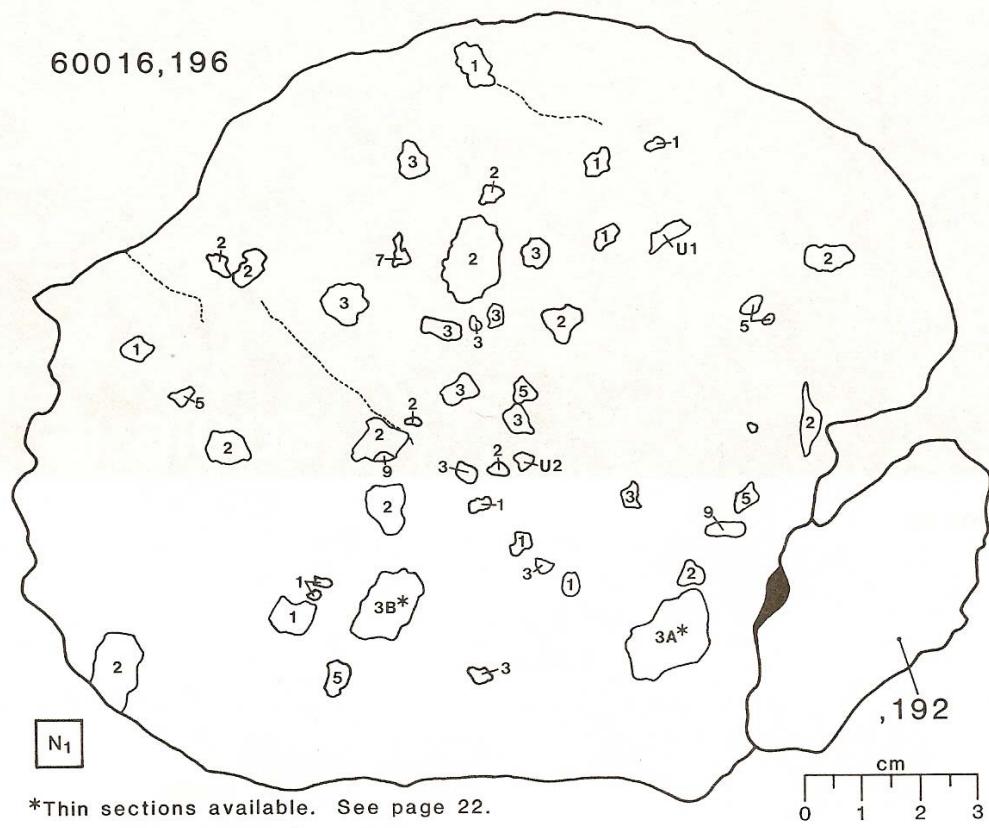


Figure 16: Photo and sketch of third slab (,196) of 60016 (Martinez 1985). S84-40920.

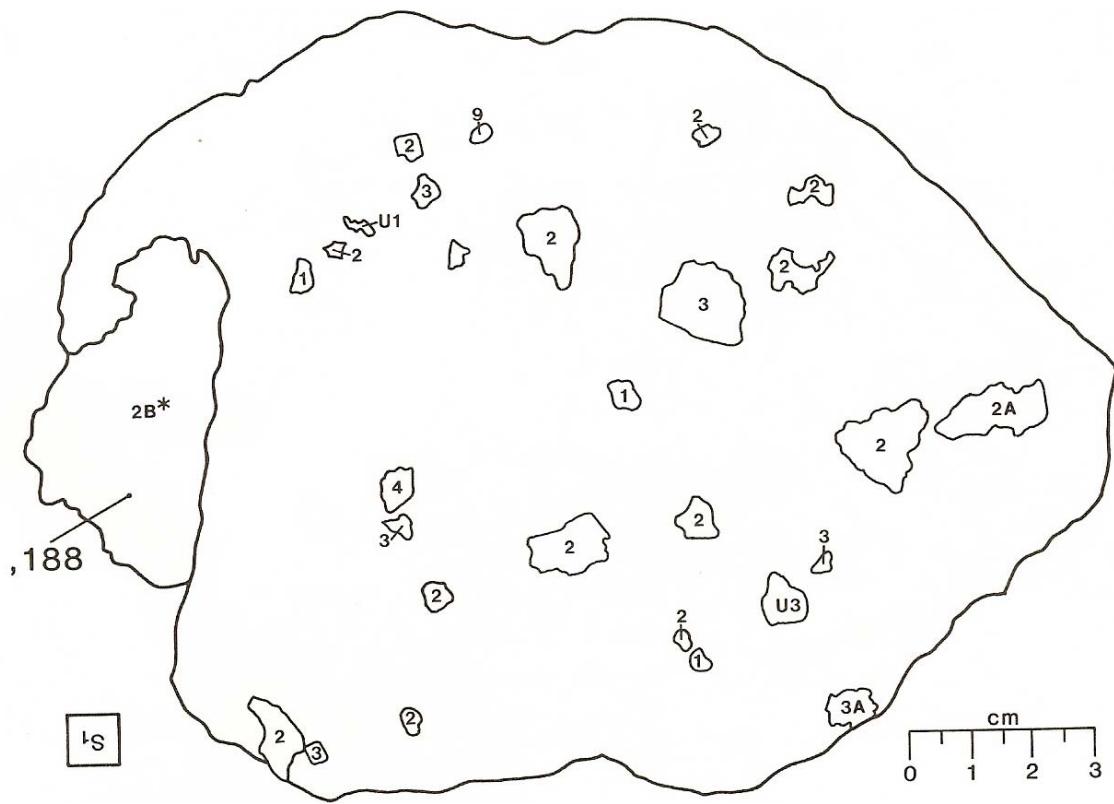
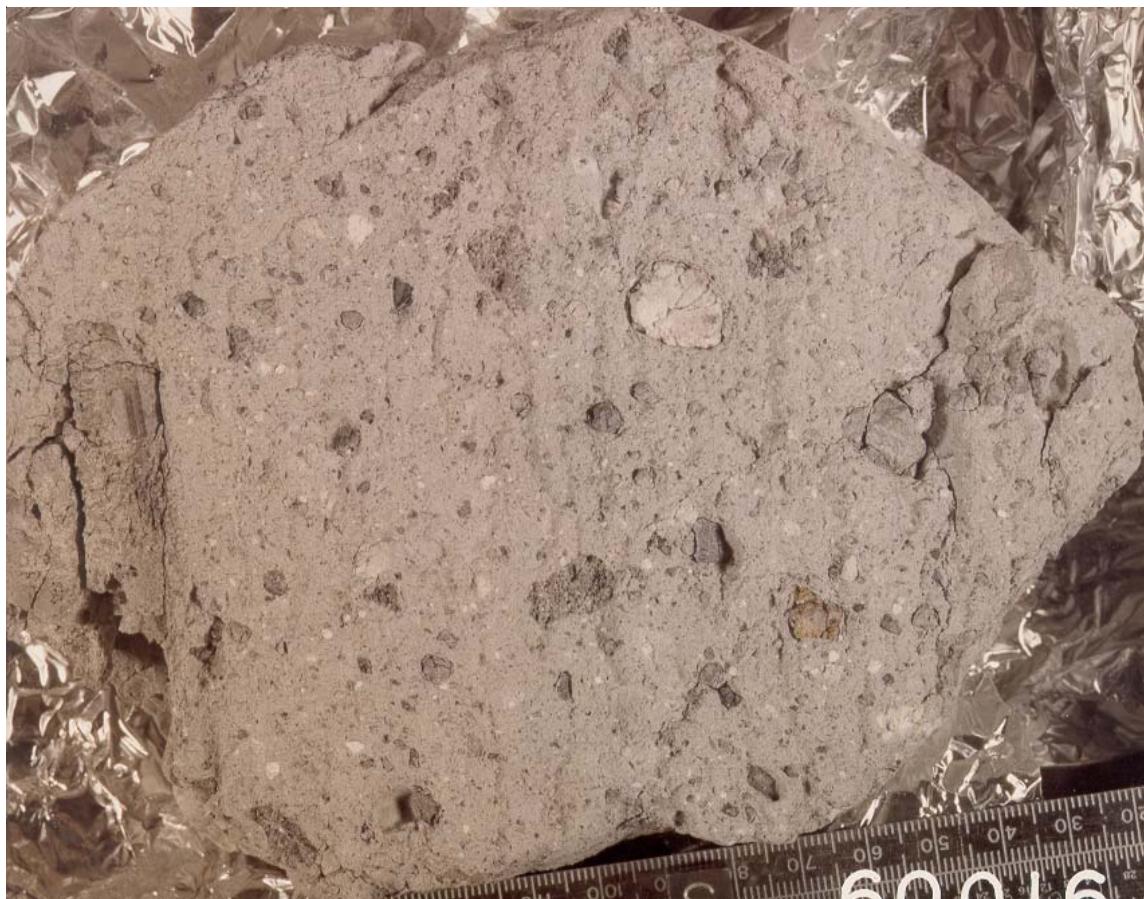


Figure 17: Photo and sketch of butt end 60016,16 after third slab removed (Martinez 1985). S84-41701. Thin sections of large clast ,188 are available.

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